Origins of the slow and the ubiquitous fast solar wind

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ABSTRACT

We present in this Letter the first coordinated radio occultation measurements and ultraviolet observations of the inner corona below 5.5 R_s, obtained during the Galileo solar conjunction in January 1997, to establish the origin of the slow solar wind. Limits on the flow speed are derived from the Doppler dimming of the resonantly scattered component of the oxygen 1032 Å and 1037 Å lines as measured with the UltraViolet Coronagraph Spectrometer (UVCS) on the Solar and Heliospheric Observatory (SOHO). White light images of the corona from the Large Angle Spectroscopic Coronagraph (LASCO) on SOHO taken simultaneously are used to place the Doppler radio scintillation and ultraviolet measurements in the context of coronal structures. These combined observations provide the first direct confirmation of the view recently proposed by Woo and Martin (1997) that the slow solar wind is associated with the axes, also known as stalks, of streamers. Furthermore, the ultraviolet observations also show how the fast solar wind is ubiquitous in the inner corona, and that a velocity shear between the fast and slow solar wind develops along the streamer stalks.

Subject headings: Sun - Corona, Sun - Solar wind

1. Introduction

The solar wind is a direct manifestation of the coronal heating processes which continue to elude us. For over three decades, observations in interplanetary space have identified two types of wind: a slow component with highly variable physical properties also characterized by speeds typically below 500 km/s, and a much less variable fast wind flowing on average at 750 km/s (e.g., Schwenn 1990; Gosling et al. 1995; Phillips et al. 1995). Connecting these two types of winds to their origins at the Sun is still not resolved. The prevailing view is that the fast solar wind observed in the ecliptic plane originates from the equatorial extensions of polar coronal holes onto the solar disk, and occasionally from equatorial coronal holes (e.g., Krieger, Timothy, & Roelof 1973; Bell and Noci 1976; Hundhausen 1977). In addition, since the boundaries of polar coronal hole do not extend below 50° latitude even at solar minimum (e.g., Harvey 1996), a faster than radial expansion of the magnetic field lines originating from the polar caps (e.g., Munro and Jackson 1977) has been recently invoked to account for the fast wind observed out of the ecliptic by Ulysses from the poles down to about 30° latitude (e.g., Gosling et al. 1995). The source of the slow solar wind, on the other hand, generally believed to be associated with the highly structured and variable streamer belt has remained more enigmatic (see, e.g., reviews by Schwenn 1990; Gosling 1997).

Important clues regarding the association of fast and slow solar wind with the corresponding magnetic field structures in the corona have recently emerged from remote sensing radio occultation measurements. Large-scale gradients in velocity indicated that the slow wind emanated from localized sources in the corona overlying the streamer belt (Woo 1995). That the slowest wind coincided with conspicuously high levels of density fluctuation characteristic of coronal streamer stalks (Woo et al. 1995) provided the first observational evidence that the streamer stalks were the sources of the slow solar wind (Woo & Martin

1997). (We refer to stalks as the narrowing of the streamers that extend into interplanetary space, as evident in solar eclipse pictures (Koutchmy 1977).) On the other hand, low levels of density fluctuations were found to be characteristic of the fast solar wind (Woo & Gazis 1993; Woo & Martin 1997), suggesting that they could be used as a proxy for the fast wind. By comparing radio ranging measurements with simultaneous white light observations, Woo and Habbal (1997) found that low levels of density fluctuations could be traced back to coronal holes as well as to quiet Sun regions (i.e. the diffuse emission seen above 10^6 K, filling the space between polar coronal holes and the active region belt). Taken together with the predominance of the fast solar wind found by Ulysses during its polar passages (Phillips et al. 1995), these results led Woo and Habbal (1997) to conclude that the fast solar wind propagates along raylike structures originating not only from polar coronal holes but also from the quiet Sun.

The advent of the Galileo solar conjunction in January 1997 and the capabilities of the UVCS (Kohl et al. 1997) offered the first opportunity to test the recent interpretations of the radio measurements. We present in this Letter the first such coordinated measurements. We show how these simultaneous observations provide the first direct confirmation that the slow solar wind is limited to the streamer stalks, while the fast wind fills the rest of the heliosphere.

2. Characteristics of UVCS Observations

UVCS on SOHO has proven to be a powerful tool for probing the physical conditions in the inner corona with measurements extending to at least 3.5 R_s in coronal holes, and to 10 R_s in denser coronal plasmas (Kohl et al. 1995, 1997; Noci et al. 1997). One of the unique advantages of this instrument is the measurement of coronal spectral lines, in particular doublets, such as the O VI 1032 Å and 1037.6 Å lines, formed primarily by the

resonance scattering of chromospheric or transition region radiation by ions flowing in the corona. Collisional excitation also contributes to the formation of these lines. As described in detail by Kohl & Withbroe (1982), Noci, Kohl, & Withbroe (1987), and Withbroe et al. (1982), the Doppler dimming effect (Hyder and Lytes 1970) is used as a diagnostic to place limits on solar wind velocities. As ions flow outwards in the corona, the fraction of the spectral line formed by resonance scattering becomes Doppler-shifted out of resonance with the disk emission. Subsequently, the relative ratio between the intensity of the lines forming a doublet changes drastically. Inferences of flow speeds from the ratio are model dependent since they are influenced by the electron density and the component of the velocity distribution in the direction of the incoming radiation to be scattered in the corona (Noci, Kohl, & Withbroe 1987).

In the case of the O VI lines, the ratio 1032/1037 equals 4 when resonant scattering is dominant, and reduces to 2 when only the collisional components are left. However, this ratio can further decrease as the flow speed increases because of the presence of a chromospheric C II line at 1037 Å . This line is redshifted by the flow and can excite the O VI 1037.6 Å line, thus leading to a "pumping" effect (Noci, Kohl, & Withbroe 1987). The Doppler dimming and pumping effects have been demonstrated successfully with UVCS in a number of coronal hole observations (Kohl et al. 1997).

The ratio 1032/1037 of 2 occurs for a flow speed of 94 km/s, corresponding to the midpoint separation (i.e. 0.3 Å) of the 1037.6 Å and 1037 Å lines, before the onset of pumping. A minimum in this ratio occurs for an ion flow speed of 180 km/s when the C II line in turn is centered on the O VI 1037.6 Å line and the pumping is at its maximum. The ratio 1032/1037 = 2 depends only on the velocity distribution along the flow direction. However, the fact that the ratio 1032/1037 in our data decreases below 2 and then increases, implies that the width of the velocity distribution along the flow direction is less than 0.6

Å otherwise, if the distribution along the flow direction were broader, the effect of the C II pumping would not be detected and the ratio would not decrease below 2. Hence, the ratio 2 used in this paper is a model independent diagnostic for an oxygen ion flow speed of 94 km/s. While the minimum in the ratio corresponding to 180 km/s is also model independent, it does not provide a wide enough mapping of the flow speed in the inner corona for the regions of interest considered in this paper.

Although the oxygen ion flow speeds could be different from the proton/electron velocity, they are still valid proxies for fast versus slow solar wind. Indeed multifluid solar wind model computations show that the flow speed of minor ions, protons and electrons are very close in values in the inner corona (Li et al. 1997).

3. UVCS Observations

Taking advantage of the diagnostic tool offered by the ratio of the oxygen lines, as well as the contrasting signatures of the fast and slow solar wind in Doppler scintillation measurements, coordinated radio occultation and UVCS observations were carried out for the first time during the Galileo spacecraft solar conjunction between 17 and 20 January 1997. Figure 1 shows an image of the corona taken with the white light coronagraph (LASCO) (Brueckner et al. 1995) on SOHO on 17 January during this observing period. The slit positions of the UVCS detector were chosen to coincide with the passage of the radio signal from Galileo through the corona starting on 17 January. The south polar coronal hole measurements on 19 January were made by UVCS alone when Galileo was occulted by the Sun. The measurements off the west limb on 20 January followed Galileo on the egress. To further map the solar wind velocity around a streamer, a second set of UVCS measurements were taken on 23, 25, and 27 April 1997. These were centered on the axis of a well-isolated streamer on the west limb at position angle PA = 267° (measured

counterclockwise from heliographic north), as well as at 20° and 40° north of that position (see Figure 2).

By measuring the intensity of the two oxygen lines and their ratio along the slits for different heliocentric distances, contours of the intensity ratio equal 2 (or equivalently an ion flow speed of 94 km/s) for the two observation sets were obtained. These are shown as white lines in Figures 1 and 2. UVCS observations away from the axes of the streamers in both data sets offered the first direct evidence for the sharp transition in flow speed near the boundary of the streamer to the ambient corona at any given heliocentric distance. A typical example illustrating this transition is shown in Figure 3 for the UVCS observations of 27 April at 3.5 R_s at 20° north of the streamer stalk shown in Figure 2. Figure 3 clearly illustrates how the relative change in peak intensity and shape of the two oxygen line profiles varies significantly as a function of latitude, or more relevantly, as a function of position angle away from the streamer stalk.

Plots of the ratio of the two oxygen lines versus heliocentric distance for different position angles SA = 0° , ± 10° and ± 20° measured north (+) or south (-) with respect to the streamer stalks are shown in Figure 4. The top three panels correspond to the January east limb observations, and the lower four panels to the April observations. For small heliocentric distances the data were averaged over 2-4'. At distances larger than 3.5 R_s the data were averaged over 11' (corresponding to an uncertainty of 2°) when the streamer stalk was not in the field of view. It is clear from these plots that the wind reaches a speed of 94 km/s (or ratio = 2) around 4.5 R_s along the streamer stalk (SA = 0°). In contrast, the wind is faster closer to the Sun as it moves away from the streamer stalk, for example, at 3.5 - 4 R_s for SA = ± 10° , or 2.5 - 3 R_s for SA = ± 20° . The first minima seen at ± 20° are very close in heliocentric distances to those found in coronal holes, and correspond to 180 km/s. An uncertainty of 0.5 in the ratio corresponds to an uncertainty of 25 km/s

in speed.

Most striking in the ratio = 2 contours is the sharp latitudinal gradient in wind speed that occurs close to the stalk of the streamers. However, not only is the change in ratio indicative of changes in solar wind character, but so is the width of the spectral lines. As shown in Figure 3, the lower ratio and broader profile are typical of a fast and hot wind (as far as the oxygen ions are concerned). These are comparable to UVCS measurements in polar coronal holes, and are a strong indication of the anisotropy of the velocity distribution in the fast wind as shown by Kohl et al. (1997). Since the line ratios are derived from measurements along the line of sight, the flow speed is high over a large fraction of the line of sight. Along the streamer stalk, on the other hand, the ratio is higher, and the lines narrower, an indication of cooler and slower flowing ions, as reported in earlier UVCS observations of streamers (Noci et al. 1997).

4. Radio Occultation Measurements

The corresponding Doppler scintillation measurements made by Galileo from 15 January to 4 February are shown in Figure 5. These measurements are normalized to heliocentric distance assuming a $1/r^2$ dependence in density fluctuation (Woo & Gazis 1993). They are characterized by relatively low levels of Doppler scintillation except on 22 January. The white light image of 22 January in Figure 6 shows that the enhanced Doppler scintillation on 22 January is caused by a streamer stalk intercepting the Galileo radio path, thus confirming that pronounced enhancements observed in Doppler scintillation in the absence of coronal mass ejections (Woo 1997) are a proxy for coronal streamer stalks (Woo et al. 1995). Results from these coordinated measurements also reinforce those obtained from comparing intensity scintillation and solar wind speed measurements (Woo & Martin 1997), i.e., low levels of Doppler scintillation observed away from streamer stalks

are a proxy for the fast wind. The use of Doppler scintillation as a proxy for wind speed is particularly important because its high sensitivity to changes in electron density over small distances makes it a measurement of high spatial resolution (Woo 1996).

5. Discussion and Conclusion

Radio occultation measurements provided the first hints of the source regions of the fast and slow solar wind and the impetus for the present coordinated observations. The results reported here illustrate the power of the UVCS instrument to provide more definitive answers, since it can map the whole plane of the sky.

Although a number of UVCS observations of streamers have been made since the launch of SOHO (see, e.g., Noci et al. 1997), the coordinated radio scintillation and ultraviolet observations of the inner corona presented here are the first of their kind. The most straightforward result to emerge from these coordinated observations is that low levels of radio scintillation are indeed associated with fast solar wind, while the pronounced peaks result from the passage of the radio signal through the streamer stalks. More importantly however, this work provides the first confirmation of the perspective recently developed from radio occultation measurements (Woo 1995; Woo & Habbal 1997; Woo & Martin 1997), namely that the streamer stalks are the locus of the slowest solar wind, while the fast solar wind dominates the corona.

These coordinated observations also confirm the existence of sharp gradients in solar wind speed found earlier by radio occultation measurements of the corona (Woo 1995), and show that they occur along the streamer stalks. Undoubtedly, remnants of this velocity shear must survive in interplanetary space since they are frequently observed in in situ observations beyond 0.3 AU (e.g. Schwenn et al. 1978; Rhodes and Smith 1981).

The UVCS observations presented here also support the view recently proposed by Woo and Habbal (1997) that the fast solar wind does not necessarily originate only from polar coronal holes; its ubiquitous nature, so vividly evident in the Ulysses measurements, can also derive from its origin in the quiet Sun regions. The fraction of the fast solar wind originating from these latter regions, however, cannot be inferred from the present observations.

That there exist two types of solar wind, namely the fast and slow, with different physical characteristics can be readily understood if we consider their corresponding magnetic sources. It seems plausible that radially extending raylike structures originate within the boundaries of supergranular cells which indiscriminately cover the solar surface in coronal holes and the quiet Sun (Title 1997). These cells are preserved in coronal holes because of the absence of large scale closed magnetic field lines. In the quiet Sun, the supergranular cells at coronal heights are essentially preserved except for occasional disruptions by large scale magnetic field lines interconnecting widely separated magnetic regions and forming its diffuse characteristic emission. Indeed, close inspection of eclipse observations of the Sun clearly show the simultaneous presence of open and closed magnetic structures along the line of sight at low latitudes (e.g. Koutchmy 1977; November & Koutchmy 1996). On the other hand, the streamer stalks which carry the slow solar wind belong to the large scale coronal structures which have dominated our impression of the corona for so long and which derive from deep-rooted multipolar fields.

The new clues provided by the results of this study should lead to new perspectives in the search for the elusive coronal heating mechanisms of the solar wind. In particular, if indeed a fraction of the fast solar wind also originates from quiet regions, then the energy flux per unit area requirements to the solar wind from its sources at the Sun can be significantly reduced.

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Fig. 1.— White light image of the corona taken with the LASCO C2 coronagraph on SOHO on 17 January 1997. The bright object in the east below the equator is Jupiter and indicates the approximate location of the Galileo spacecraft. The field of view spans 2 to 6 R_s. The spatial length of the field of view defined by the slit of the UVCS detector is approximately 2 R_s. Shown as black vertical lines are the slit positions, located at 1.9, 2.5, 3, 4, 4.7 and 5.5 R_s on the east limb, at 1.9 R_s in the south polar coronal hole, and at 4, 4.7 and 5.5 R_s at the west limb. They are perpendicular to the radial direction at position angles PA = 97° , 180° and 247° respectively, measured counterclockwise from heliographic north. The white contours mark the ratio of the oxygen 1032/1037 line intensities equal to 2, or, equivalently 94 km/s.

Fig. 2.— Same as Figure 1 for observations on 23, 25 and 27 April, 1997. The background white light corona from LASCO was taken on 27 April. These observations were made with slit positions perpendicular to the axis of the streamer at PA = 267° at 2.3, 3., 3.5, 4., 4.5, and 5 R_s. Additional observations were made at 20° north of these positions and one at 40° north of the position at 3 R_s. Here too the white contours mark the ratio of the oxygen 1032/1037 line intensities equal to 2.

Fig. 3.— Top panel: False-color image of the intensity of the O VI 1032 Å , 1037.6 Å and Ly β lines along the detector slit (or spatial direction/vertical axis) positioned at 3.5 R_s, 20° north of the streamer axis of Figure 2. The horizontal axis is the spectral direction. The resolution of a bin element is 0.28 Å in the spectral direction (1 bin = 2 detector pixels) and 28" in the spatial direction. Tick marks are spaced approximately every 1 Å and 1' in the spatial and spectral directions respectively. Note that because of the pointing on 27 April, the roll angle of UVCS is such that north faces downward in this figure. Bottom panels: Profiles of the 1032 Å (left) and 1037.6 Å (right) lines averaged over (a) 4.5', (b) 5.25' and (c) 11.5', as indicated by the corresponding labeled spaces between the arrows in the top

panel. The scale on the horizontal axis is in detector pixel (or 0.14 Å). The ratio of the line intensities is (a) 2.1 ± 0.1, (b) 1.7 ± 0.25 and (c) 1.4 ± 0.5 respectively, indicating an increase in flow speed from (a) to (c).

Fig. 4.— Plots of the ratio of the two oxygen lines versus heliocentric distance R/R_s for different position angles SA = 0° , ± 10° and ± 20° measured north (+) or south (-) with respect to the streamer stalk. Panels (a)-(c) correspond to the January east limb observations, and (d)-(g) refer to the April observations.

Fig. 5.— Radio Doppler scintillation measurements by Galileo during its solar conjunction from 15 January to 4 February 1997, or day of year (doy) 15 to 35.

Fig. 6.— White light image on 22 January 1997 from the LASCO C3 coronagraph, with a field of view extending from 3.7 to 30 R_s. Jupiter (the bright object) indicates the point of closest approach of the line of sight radio path from Galileo.

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